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# Wear and corrosion protection in roller bearings – Influence of ratio between extreme pressure / anti wear additive and corrosion inhibitor

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ABSTRACT

Roller bearings are lubricated with oils or greases containing several additives to reduce wear and corrosion. Given that almost 50% of bearing failures arise from abrasive/adhesive wear and moisture-induced corrosion, the combined role of EP/AW additives and corrosion inhibitors (CIs) is crucial. However, their polar nature indicates potential antagonism when CIs are combined with EP/AW-containing oils. The impact of simultaneous EP/AW and CI use on corrosion resistance remains unknown. This study presents a novel corrosion protection test to evaluate this interaction. Furthermore, studies on other additive combination demonstrate the importance of the ratio between additives for optimum functionality. Therefore, the effect of the CI ratio to EP/AW on wear and corrosion protection is also being studied. The results clearly recommend the addition of 0.5 wt% CI when using 1.0 wt% EP/AW in order to achieve a good compromise between wear and corrosion protection.

## 1. Introduction

Machine elements are lubricated with oil or greases to reduce wear. In addition to the base oil, these lubricating oils contain various additives to secure high performances. Interactions between additives are possible, which can result in synergistic effects, enhancing each other's performances, or antagonistic effects by hindering the functionality of the other additive [1]. Several studies reported synergistic as well as antagonistic effects, which influenced the performance of extreme pressure / anti wear (EP/AW) additives. For instance, the effectiveness of zinc dialkyl dithiophosphate (ZDDP) can be improved through the use of friction modifier additives [2,3]. On the other hand, the addition of dispersants may slow down the tribological boundary layer (TBL) formation rate of ZDDP [4,5]. A study by SKF revealed that almost 50% of roller bearings fail due to abrasive/adhesive wear and moisture corrosion [6], which shows the relevance of properly working EP/AW additives and corrosion inhibitors (CI) in the lubrication of roller bearings. An antagonistic effect is to be expected due to the polar properties of both additives competing for the metal surface [1,7,8] and first investigations show a reduction of the failure load stage in a standardized FZG test rig according to DIN ISO 14635–1 [9] when CI is added to an EP/AW containing oil [8,10]. Although general antagonistic effects have been reported and CIs are required in addition to EP/AW additives in roller bearings, the influence of CI when used combined with EP/AW has not yet been systematically clarified. Therefore, Reimers et. al. firstly introduced a method to investigate the influence of CI on the wear protection of EP/AW using an axial thrust bearing test rig and micro analyzing method such as electron probe micro analysis (EPMA) [11]. Using this method, they showed a positive effect of CI zinc carboxylate (CI) and a negative effect of calcium sulfonate (CI) on the wear protection of primary ZDDP (EP/AW) [12]. Furthermore, the effect on the formed TBL was shown, which not only influence the wear protection but also the corrosion protection. However, the influence of simultaneous use of EP/AW and CI on the resulting corrosion protection remains unknown. Therefore, in this study a novel corrosion protection test will be introduced and utilized to show the influence of the TBL generated by the simultaneous use of EP/AW and CI on the resulting corrosion protection. The results in [12] base on an additive ratio of 1.0 wt% EP/AW and 0.5 wt% CI. Studies on different additive interactions show the relevance of the ratio between the additives for an optimal functionality [13,14]. Therefore, additionally the effect of the CI ratio to EP/AW on the wear and corrosion protection will be analyzed in this study. Finally, the results will be correlated to find a good compromise between wear and corrosion protection.

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**Nomenclature**

*Latin characters*

| | |
|---|---|
| $F$ | Force [kN] |
| $n$ | Rotational speed [$\text{min}^{-1}$] |
| $T$ | Temperature [°C] |
| $t$ | Test duration [h] |

*Abbreviations*

| | |
|---|---|
| BSE | Backscattered electron |
| CaSulf | Calcium sulfonate |
| CI | Corrosion inhibitor |
| CPT | Corrosion protection test |
| EDX | Energy dispersive x-ray |
| EP/AW | Extreme pressure / anti wear |
| EPMA | Electron probe microanalysis |
| FIB | Focused Ion Beam |
| SE | Secondary electron |
| TBL | Tribological boundary layer |
| TEM | Transmission electron microscopy |
| WDS | Wavelength-dispersive spectrometers |
| ZDDP | Zinc dialkyl dithiophosphate |
| ZnCarb | Zinc carboxylate |

## 2. Materials and methods

The influence of the CI ratio was investigated for two different additive combinations. A more detailed description of the base oil and additives can be found in Chapter 2.1. The effect on the wear protection for highly loaded rolling contacts is evaluated in an axial thrust bearing test rig (FE8) according to DIN 51819–3 [15]. The FE8 test setup and the corresponding test conditions are defined in Chapter 2.2. To investigate the corrosion protection provided by the formed TBL, a novel corrosion protection test (CPT) was developed and introduced in Chapter 2.3. Electron probe microanalysis (EPMA) and FIB-TEM were used to examine the TBL on the rolling elements. These analytical methods are described further in Chapter 2.4.

### 2.1. Base oil and additives

The oils consist of base oil, 1.0 wt% EP/AW and either none, 0.25 wt %, or 0.5 wt% CI. A mineral oil (API group I) of the viscosity class ISO VG 100 is used as base oil a primary zinc dialkyl dithiophosphate (ZDDP) with a C8 chain containing of 8 wt% phosphorus, 16 wt% sulfur, and 9.5 wt% zinc as EP/AW. As CI either calcium sulfonate (dialkyl benzene sulfonate) containing of 2 wt% calcium or zinc carboxylate (2-ethylhexanoic acid) consisting of 15 wt% zinc was combined with the ZDDP. In this study, the abbreviations CaSulf (calcium sulfonate) and ZnCarb (zinc carboxylate) will be used. Table 1 provides an overview of the oils investigated. For both CIs, no chemical reaction with the selected EP/AW is anticipated in the oil solution, as these additive combinations are found in commercially available additive packages. Consequently, these additive combinations allow the study of how CIs influence the formation of TBL of the EP/AW and therefore the wear and corrosion protection provided by simultaneous use of EP/AW and CI.

**Table 1**
Analysed oils.

| Oil | Base oil | EP/AW | CI |
|---|---|---|---|
| 1 | mineral oil | 1.0 wt% ZDDP | none |
| 2 | (API group I, ISO VG 100) | | 0.25 wt% CaSulf |
| 3 | | | 0.50 wt% CaSulf |
| 4 | | | none |
| 5 | | | 0.25 wt% ZnCarb |
| 6 | | | 0.50 wt% ZnCarb |

### 2.2. Wear protection test setup

To evaluate the effect of CI on the wear protection performance of EP/AW in high-load oil-lubricated rolling bearings, FE8 tests were conducted in accordance with DIN 51819–3 [15]. The FE8 test rig was equipped with axial cylindrical roller bearings (type 81212). Each bearing comprises 15 rolling elements, two washers, and a cage. The rolling elements and washers were manufactured from 100Cr6, while a polyamide cage (PA66) was selected to prevent potential chemical interactions that could occur with alternative cage materials such as brass. Rolling elements and washers with an arithmetic mean roughness (Ra) of 0.04–0.05 μm were used to minimize the influence of surface roughness on the wear test results. In each FE8 test, two bearings of the described type were tested simultaneously under a constant load, which is applied by a hydraulic system. Each bearing was individually supplied with oil at a flow rate of 0.1 L/min. During testing, the shaft was run at the specified rotational speed. The required bearing temperature was controlled using a heating jacket during testing. The test rig and bearing configuration are illustrated in Fig. 1a. Due to the geometry of the axial thrust bearing, different slide–roll ratios (SRR) occur along the width of the rolling elements, as shown in Fig. 1b.

The FE8 tests were evaluated based on the wear mass of rolling element sets, each of which consisted of 15 rolling elements. Each set was weighed before and after testing with an accuracy of 1 mg. Additionally, each FE8 test included two test bearings that were analyzed separately. To assess the influence of CI on the wear protection of EP/AW, the mean wear values of the rolling element sets from both test bearings were calculated for comparison. Due to its good reproducibility, each test was conducted once, as indicated in [16,17]. To prevent cross-contamination from previous tests, the test rig was cleaned and flushed with new oil before each experiment. Then, the test rig was cleaned again before being filled with the oil intended for the test.

As described in the previous study [11], two different test conditions are required for a combined investigation of the impact of CI on the wear protection of EP/AW in oil-lubricated roller bearings. With the standardized FE8 test conditions (7.5 $\text{min}^{-1}$, 80 kN, 80 °C, 80 h, $\lambda \approx 0.05$) according to DIN 51819–3 [15], in the following referred to as *wear test*, the influence on the wear protection can be observed. However, no additive element rich TBLs were formed under *wear test* conditions with the oils analyzed. This additive element rich TBL is necessary for evaluating the CI influence on EP/AW and for assessing corrosion protection. Therefore, FE8 tests with adapted test conditions using accelerated speed (75 $\text{min}^{-1}$, 80 kN, 80 °C, 80 h, $\lambda \approx 0.2$) according to [18], in the following referred to as *run-in test*, are conducted. Since the *run-in test* is conducted under less severe conditions than the *wear test*, significant differences in wear losses between the oils are not expected in the *run-in test*. This underscores the necessity of conducting a *wear test*. An overview of the two FE8 test conditions and the corresponding possible analyzing methods are shown in Table 2.

### 2.3. Novel corrosion protection test setup

The corrosion protection characteristic of an oil in presence of water is usually determined using the standard corrosion test according to ISO 7120 [19]. In this study, this methodology was modified as the focus is to analyze the corrosion protection of the TBL formed in FE8 test. A novel corrosion protection test (CPT) was developed. Instead of an unalloyed carbon steel the rolling elements with TBL formed in the *run-in test* (FE8) was used as test specimen in the novel CPT. The rolling elements were exposed to an oil-water-emulsion with an oil-water ratio of 10:1 at 60 °C for 24 h. To ensure a homogeneous emulsion, a stirrer rotates constantly with 1000 $\text{min}^{-1}$. Instead of the oil including additives tested in the standard, the novel CPT only uses base oil without

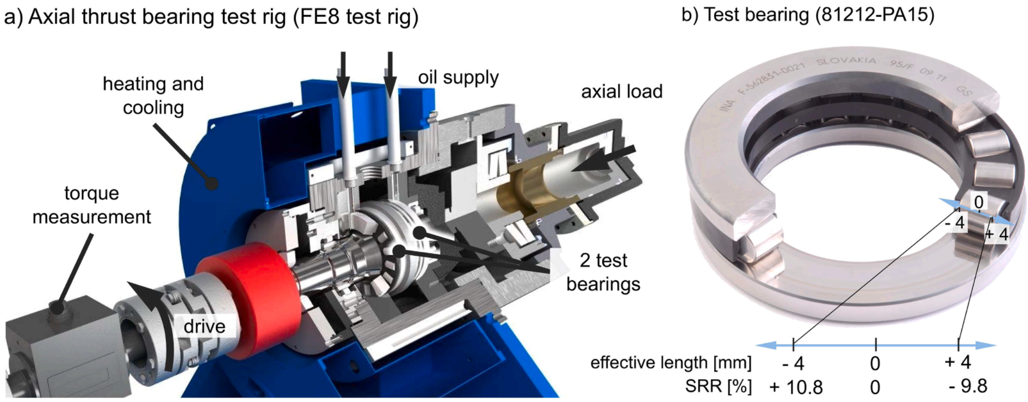


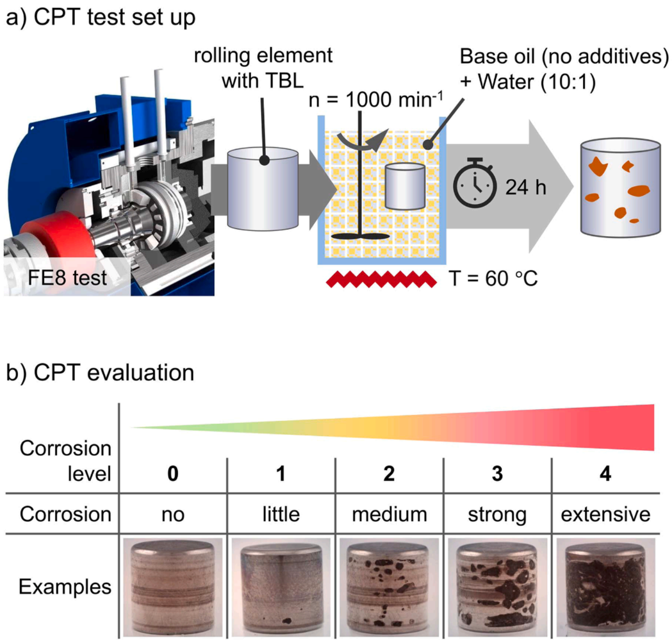
**Fig. 1.** FE8 test rig and test bearing.

**Table 2**
FE8 test conditions and corresponding analysing methods.

| | **FE8 test conditions** | | **Analyzing methods** | | |
|---|---|---|---|---|---|
| | **Speed** | **Constants** | **Wear Protection (FE8)** | **Tribofilm characterization (EPMA)** | **Corrosion Protection (CPT)** |
| ***Wear test*** | 7.5 min$^{-1}$ | F = 80 kN<br>($p_{Hertz}$ = 1.89 GPa)<br>T = 80 °C<br>t = 80 h | yes | limited | limited |
| ***Run-in test*** | 75 min$^{-1}$ | | limited | yes | yes |

additives. This ensures an evaluation of the TBL formed on the rolling element when using EP/AW and CI simultaneously, which is the focus of this study. To prevent corrosion of the blank end faces of the rolling elements, the holder was designed so that these faces, including the chamfers, are completely covered and only the running surface with the TBL is exposed to the oil-water-emulsion. The CPT test set up is shown in Fig. 2a.

The corrosion protection of TBL formed in FE8 is visually evaluated with a corrosion level from 0 (no corrosion) to 4 (extensive corrosion). Due to the different visual appearances of the TBLs, it is difficult to reproducibly determine the corroded areas by means of image processing. For this reason, manual evaluation by means of exemplary images for each corrosion level is used in this study. From each FE8 test two rolling elements are rated in the CPT test. The average of the corrosion level of the rolling elements results in the total corrosion level for one FE8 test. The CPT evaluation with the 5 corrosion levels including example pictures are shown Fig. 2b.



| Corrosion level | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Corrosion | no | little | medium | strong | extensive |
| Examples | | | | | |

**Fig. 2.** Corrosion Protection test a) set up and b) evaluation matrix.

### 2.4. Analyzing methods of TBL

The TBL formed on the rolling elements was analyzed by electron probe microanalysis (EPMA). EPMA is a non-destructive method for studying element coverages along the whole surface of the rolling element. The measurement was performed in a microprobe of the type JXA 8500 F equipped with a Schottky Field Emitter and five wavelength-dispersive spectrometers (WDS). The advantage of the WDS-technique is the high spectral resolution which delivers accurate oxygen values and low detectable element-specific coverages. Low detection limits are needed for studying the behavior of the additive elements in the formation of the TBL layer. A series of data points were acquired along the whole width of the rolling bearing with a step width of 140 μm. The beam diameter/probe was defocused to a diameter of 10 μm to average over roughness induced signal variations. In Fig. 3 an exemplary result of an EPMA measurement is shown: Mass coverages of the elements Zn, S, P, Ca and O versus distance of the line profile. After the corrosion tests EPMA was applied nearby the corroded area and a shorter scan with denser data points was measured to reveal the various stages of corrosion damage.

In a second step the TBL was investigated by Transmission Electron Microscopy (TEM), to study the nano-layered structure of the TBL formed on the rolling elements after the *run-in tests*. For the specimen preparation thin lamellae were cut by a Focused Ion Beam (FIB) workstation in a region of high SRR. To protect the surface of the TBL a Pt-layer was deposited in the FIB. The deposition procedure consisted of 2 steps: at first electron-beam-induced and then ion-beam-induced deposition. For image acquisition conventional TEM and for analytical purposes an EDX-detector was used on a FEI Tecnai F20.

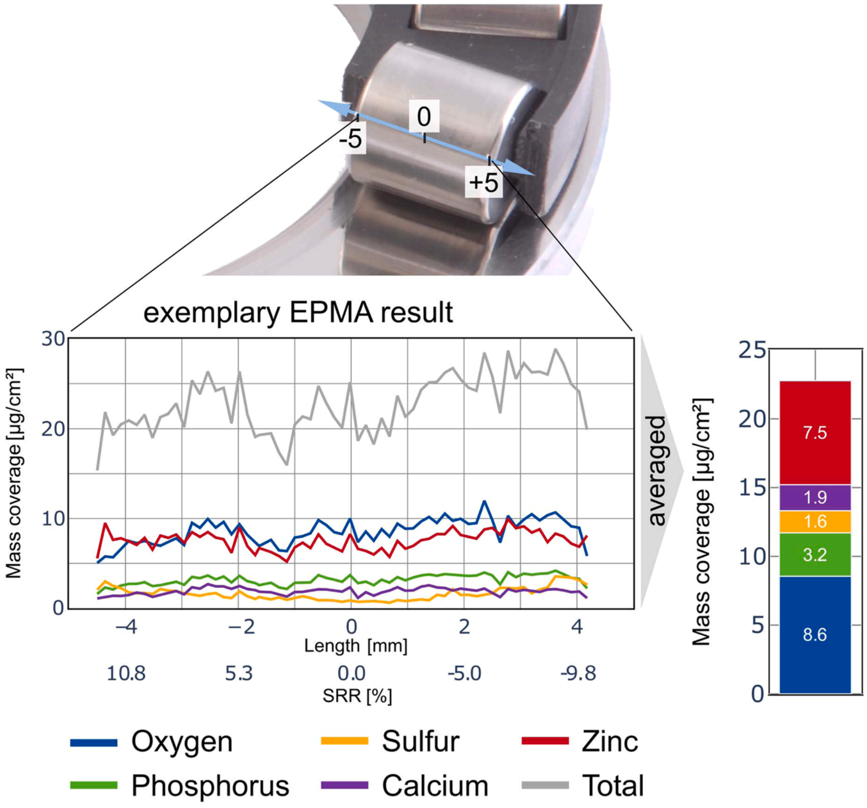


**Fig. 3.** Representation of the EPMA results.

## 3. Results

First, the results of the wear protection test using FE8 are presented (chapter 3.1) followed by the results from the novel corrosion protection test (chapter 3.2). Finally, the microanalysis of the TBL after the wear and corrosion protection test are shown (chapter 3.3).

### *3.1. Wear protection test*

The wear masses of the *run-in* test are visualized in Fig. 4a. With an increase of the ratio of calcium sulfonate the wear masses increase, which results in a reduction in wear protection. In the previous study [12] a negative influence of the CI calcium sulfonate on the wear protection of ZDDP was shown. The negative trend in the wear masses was already visible in the less harsh *run-in test* with 1.0 wt% ZDDP and 0.5 wt % CaSulf. Furthermore, the wear masses in the *wear test* for 1.0 wt% ZDDP and no calcium sulfonate as well as with 0.5 wt% calcium sulfonate were higher than 1000 mg, which is why the negative effect of calcium sulfonate was not visible in the *wear test*. On the basis of these results the influence of ratio of calcium sulfonate is analyzed in the *run-in test*.

A positive effect of the CI zinc carboxylate on the wear protection of ZDDP was shown in the previous study [12]. However, the *wear test* was necessary to show this effect. Also, to reveal the effect of the ratio of zinc carboxylate no significant differences in the wear masses can be observed in *run-in test* (Fig. 4a), which is why *wear tests* have been conducted with ZDDP + zinc carboxylate (Fig. 4b). The results show already a significant decrease in the wear mass when adding a small ratio of 0.25 wt% zinc carboxylate to 1.0 wt% ZDDP and thus a significant increase in wear protection. Further reduction in the wear mass can be achieved with a higher ratio of 0.5 wt% zinc carboxylate added to 1.0 wt% ZDDP. However, the difference in wear masses is not too great between 0.25 wt% and 0.5 wt% of zinc carboxylate added to 1.0 wt% ZDDP.

### *3.2. Novel corrosion protection test*

Without any CI, the TBL formed in FE8 with ZDDP only shows medium corrosion, which results in a corrosion level 2. When adding either 0.25 wt% calcium sulfonate or 0.25 wt% zinc carboxylate the corrosion level decreases and thus, the corrosion protection properties of the corresponding TBLs increase. There is however a significant reduction in the corrosion protection when 0.5 wt% CI is added. This applies to both CI zinc carboxylate and calcium sulfonate. The results in the form of corrosion level of the CPT are shown in Fig. 5a with the corresponding pictures of the corroded rolling element in Fig. 5b.

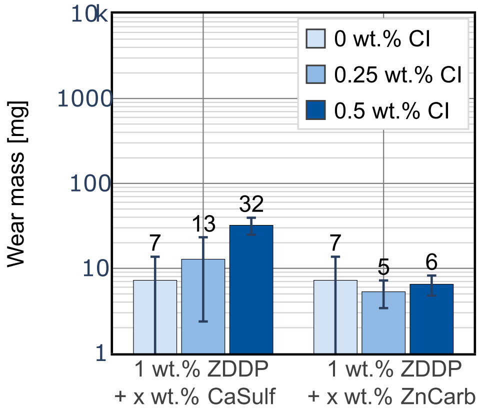
### *3.3. Microanalysis of TBL*

In Fig. 6a the mass coverage and mass concentration of oxygen as well as of the additive elements averaged over the whole length of the surface of the rolling elements are presented for the different calcium sulfonate ratios.

With higher calcium sulfonate ratio, the Ca and P mass concentration is increasing whereas the Zn mass concentration is decreasing. This observation can be explained by formation of Ca-phosphate phases in the TBL. It was confirmed by EDX-analysis in Scanning-TEM-Modus (Fig. 7). The beam was scanned in a small rectangular area nearby the surface (red rectangle) and nearby the interface to the substrate 100Cr (blue rectangle) and simultaneously energy-dispersive spectra were acquired. Zn, S and O were mainly detected in the surface-near region whereas Ca-, P- and O x-ray lines appear nearby the interface.

Even though no significant differences in wear masses were observed with the addition of different concentrations of ZnCarb in the *run-in test*, difference can be seen in the TBL formed (Fig. 6a). The oxygen content of the TBL is increasing by almost a factor 2 when adding 0.5 wt% zinc carboxylate. The extreme increase can be explained by TEM combined with EDX measurements (Fig. 7). For the measurements a thin lamella was cut at a length (see Fig. 3) of about −2 mm. The corresponding

a) ***run-in test*** *(n = 75 min$^{-1}$)*



b) ***wear test*** *(n = 7.5 min$^{-1}$)*

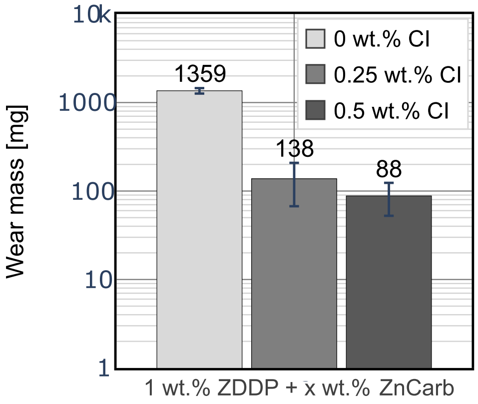
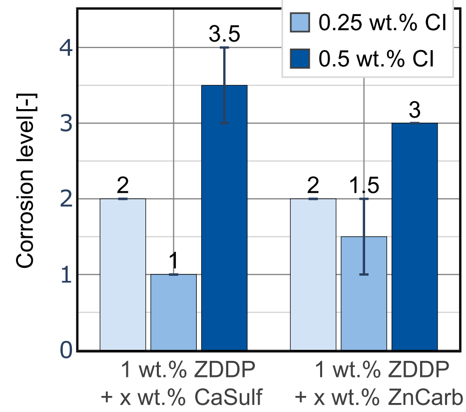


**Fig. 4.** FE8 test results for a) run-in test and b) wear test.

bright-field image shows clearly two layers forming when adding zinc carboxylate. It should be particularly highlighted that the lower layer consists mainly of iron and oxygen induced by zinc carboxylate, while the upper layer consists mainly ZDDP elements such as phosphorus and zinc. When adding a small ratio of 0.25 wt% zinc carboxylate to 1.0 wt% ZDDP, a significant increase in the oxygen content in TBL after *wear test* as well as no phosphorus and sulfur can be observed, which elements are related to ZDDP (Fig. 6b). Furthermore, the addition of zinc carboxylate results in the formation of a homogeneous TBL across the entire rolling element width, whereas with ZDDP solely, no homogeneous TBL could be formed in the *wear test*. The corresponding Fig. 12 with the EPMA results over the rolling element width is added to the appendix. The TBL after the *wear test* with the ratio of 0.25 wt% and 0.5 wt% zinc carboxylate do not differ significantly regarding the averaged mass coverage.

Further measurements of the corroded surfaces have been made to investigate the corrosion effect for the test with none, 0.5 wt% calcium sulfonate and 0.5 wt% zinc carboxylate. In Fig. 8 EPMA line scans start at the corroded area and cross the surrounding region. The corroded area is visible as heavily roughened surface in the secondary electron (SE)-image. In all three cases a high oxygen level reveals the formation of Fe-oxide or Fe-hydroxide which is the typical pitting corrosion phenomena. At the edge of the corroded area almost no additive elements and oxygen are detected for the roller bearings from the test with none or 0.5 wt% calcium sulfonate. There the TBL was eroded and an almost pure metal surface remained, visible by a brighter region in the backscattered electron (BSE)-image. In the case of adding 0.5 wt% zinc carboxylate this region still has some oxygen left pointing to the original two-layered structure described in this chapter where the upper TBL layer was only removed. The thin Fe-oxide layer containing some Cr (see energy-dispersive spectrum of Fig. 7c) might act as passivation layer in the beginning of corrosion.

a) Corrosion level



b) Rolling elements after CPT

| x | 1 wt.% ZDDP + x wt.% CaSulf | 1 wt.% ZDDP + x wt.% ZnCarb |
|---|---|---|
| 0.0 |  |  |
| 0.25 |  |  |
| 0.5 |  |  |

**Fig. 5.** Corrosion protection test results.

## 4. Discussion

The test results presented in chapter 3 demonstrate the varying effects of CI ratio on wear and corrosion as well in the formed TBL. A correlation of the results is therefore carried out for calcium sulfonate and zinc carboxylate separately regarding the effect of CI ratio on both wear and corrosion protection. For all test the concentration of ZDDP was kept constant at 1.0 wt%.

### *4.1. Influence of calcium sulfonate ratio*

When increasing the calcium sulfonate ratio, the wear protection decreases. This correlates with an increase in proportional more calcium and phosphorous and proportional less zinc embedded in the TBL. EDX (Fig. 7) analysis show the formation of calcium phosphate and less zinc phosphate when calcium sulfonate was added. The formation of the wear critical calcium phosphate [20] and less zinc phosphate, which usually gets formed by ZDDP and prevents wear [21,22], explains most likely the higher wear caused by the addition of CI calcium sulfonate. Even though wear protection steadily decreases with increasing CI

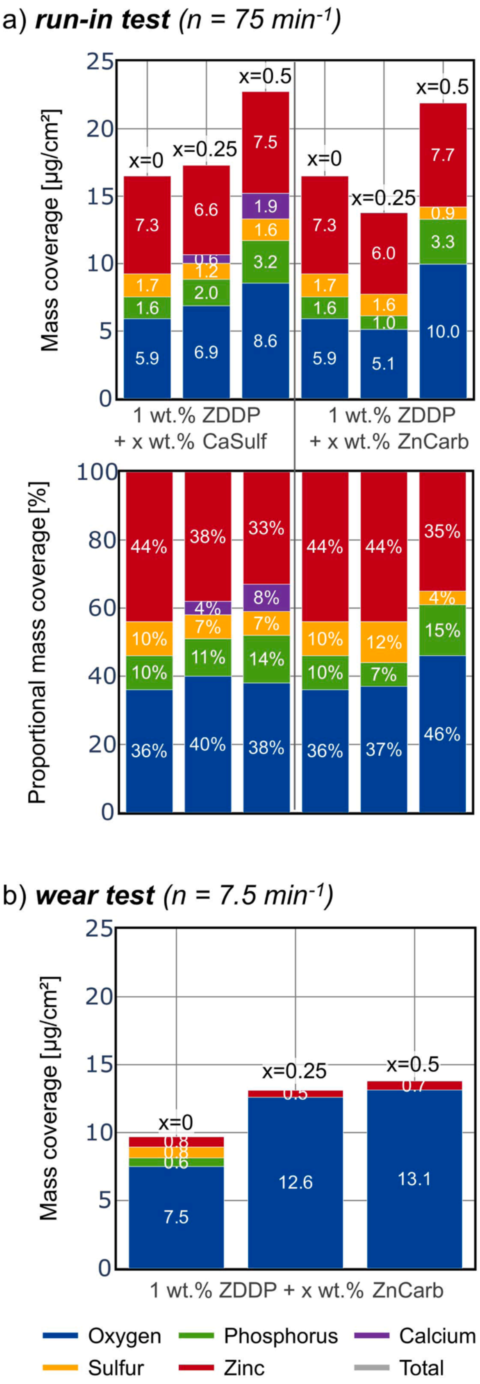


**Fig. 6.** Averaged EPMA results of TBL formed in a) run-in test and b) wear test.

calcium sulfonate, this does not apply to corrosion protection. By adding 0.25 wt% CI calcium sulfonate the corrosion protection increases as expected. However, by increasing the calcium sulfonate ratio further to 0.5 wt%, the corrosion protection decreases significantly, dropping even below the corrosion protection provided by ZDDP solely. This can most likely be explain by a poor quality of the TBL in terms of a more inhomogeneous TBL, which is formed when adding 0.5 wt% calcium sulfonate shown in the previous study [12]. A surface that is not completely covered provides a potential contact point for water with metal, corrosion can form and undermine the TBL.

Overall, the correlated results show a good compromise between wear and corrosion protection when using 1.0 wt% ZDDP and 0.25 wt% calcium sulfonate. The correlated results for the effect of calcium sulfonate ratio are visualized in Fig. 9a.

### 4.2. *Influence of zinc carboxylate ratio*

The wear protection in *wear test* increases significantly, when already a small ratio of 0.25 wt% zinc carboxylate is added. This correlates with a high oxygen content of the TBL. The significant more homogeneous TBL with 0.25 wt% zinc carboxylate compared to ZDDP solely dominates the wear protection. Due to the high oxygen content in the TBL when adding ZnCarb, an additional *wear test* was carried out using only 0.5 wt% ZnCarb without ZDDP. The results are shown in Fig. 10a with the corresponding EPMA results in Fig. 10b. The EPMA linescan is added to the Appendix in Fig. 13. It has been demonstrated that the wear protection achieved with ZnCarb alone is equivalent to that obtained through the combination of ZDDP and ZnCarb. The TBL of ZnCarb alone and in combination with ZDDP is similar, indicating that ZnCarb alone forms an oxygen-rich TBL and therefore is responsible for a better wear protection.

In run-in test the wear protection does not differ significantly for different ZnCarb ratio compared to ZDDP solely. Consequently, the top layer, which resembles a typical ZDDP layer, provides the same protection against wear as ZDDP solely. Even though wear protection does not change significantly with increasing zinc carboxylate, this does not apply to corrosion protection. Firstly, by adding 0.25 wt% zinc carboxylate the corrosion protection increases as expected. However, by increasing the zinc carboxylate ratio further to 0.5 wt%, the corrosion protection decreases even below the corrosion protection provided by ZDDP solely as it was with calcium sulfonate.

Overall, the correlated results show a very good compromise between wear and corrosion protection when using 1.0 wt% ZDDP and 0.25 wt% zinc carboxylate. The correlated results for the effect of zinc carboxylate ratio are visualized in Fig. 9b.

## 5. Conclusion

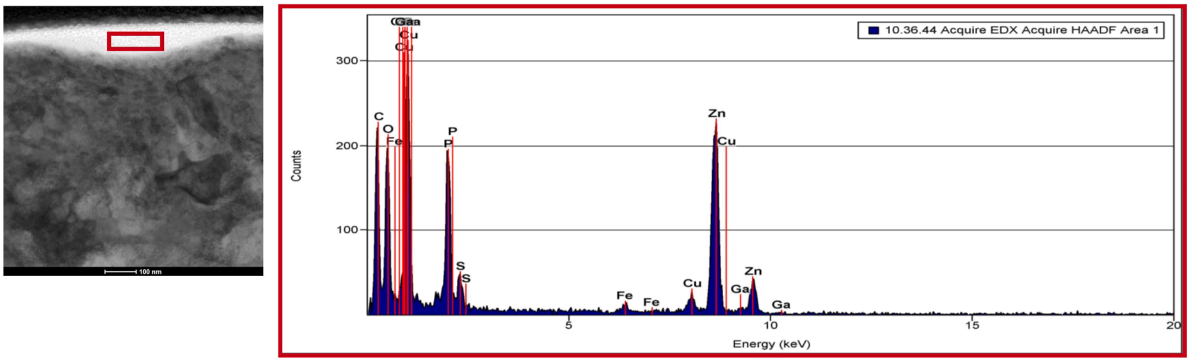
In addition to EP/AW additives, CI additives are required in machine elements such as roller element bearings. First investigations show synergistic as well as antagonistic effects when using EP/AW and CI simultaneously [12]. The influence of the CI ratio to EP/AW on wear and corrosion protection was investigated in this study in order to find a good compromise between wear and corrosion protection. The results of this study enable the following conclusions to be drawn:

- Monotonic relation between CI ratio and resulting wear protection
  - o Higher ratio of CI calcium sulfonate decreases wear protection.
  - o Already a small ratio of 0.25 wt% zinc carboxylate increases the wear protection in *wear test* significantly. However, with higher rotational speed no significant difference in wear protection can be seen when adding zinc carboxylate regardless of the ratio.
- A method for evaluating the corrosion protection of formed TBL was developed and introduced.
- Non-monotonic relation between CI ratio and resulting corrosion protection:
  - o Adding 0.25 wt% CI results in better corrosion protection compared to ZDDP solely.
  - o By adding excessive amount of CI (0.5 wt%) the corrosion protection is even worse compared to ZDDP solely.
- The Addition of CI calcium sulfonate forms wear critical calcium phosphate embedded in TBL.
- The Addition of CI zinc carboxylate forms two-layered TBL.

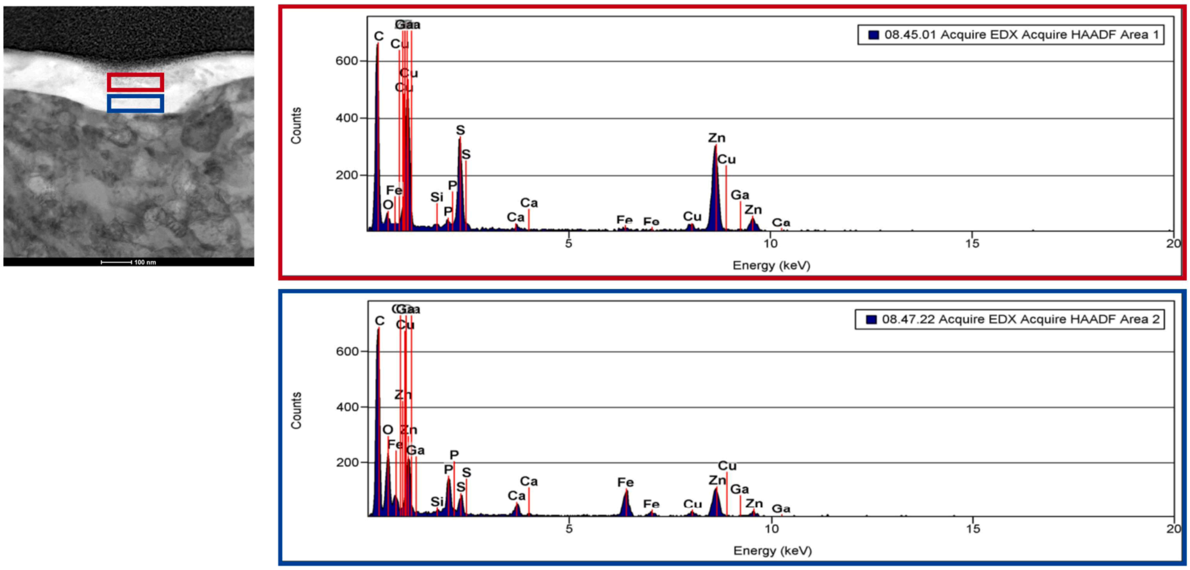
Overall, the findings clearly recommend the addition of 0.25 wt% CI to 1 wt% ZDDP in order to achieve a good compromise between wear and corrosion protection.

Supplementary studies around the range of 0.25 wt% CI are needed to identify the optimum CI ratio for wear and corrosion protection with

a) 1 wt.% ZDDP (no CI)



b) 1 wt.% ZDDP + 0.5 wt.% CaSulf



c) 1 wt.% ZDDP + 0.5 wt.% ZnCarb

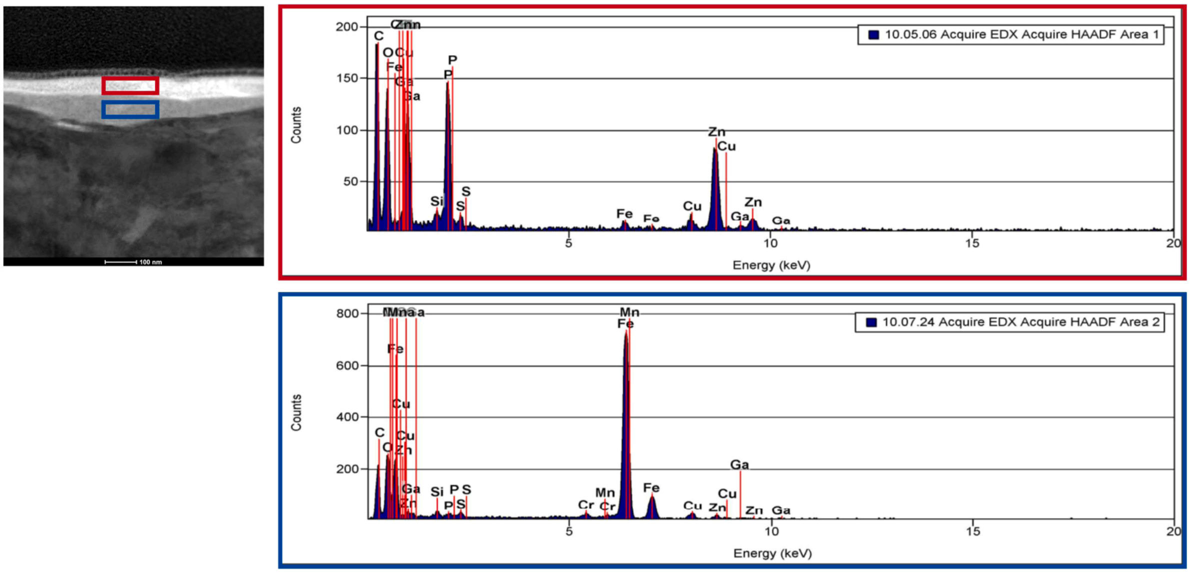
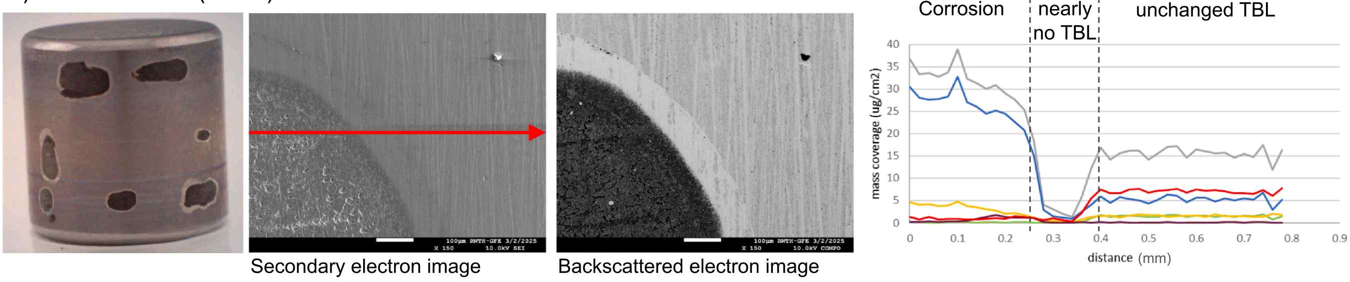
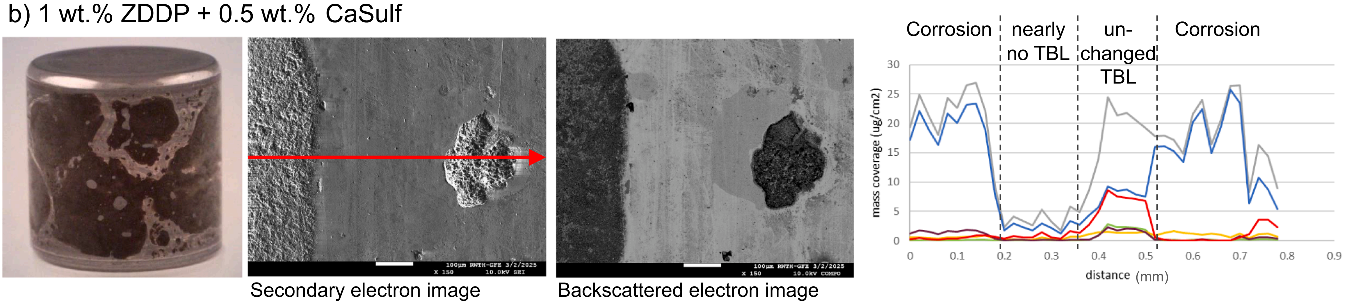


**Fig. 7.** EDX results of TBL formed in run-in test.

a) 1 wt.% ZDDP (no CI)



b) 1 wt.% ZDDP + 0.5 wt.% CaSulf



c) 1 wt.% ZDDP + 0.5 wt.% ZnCarb

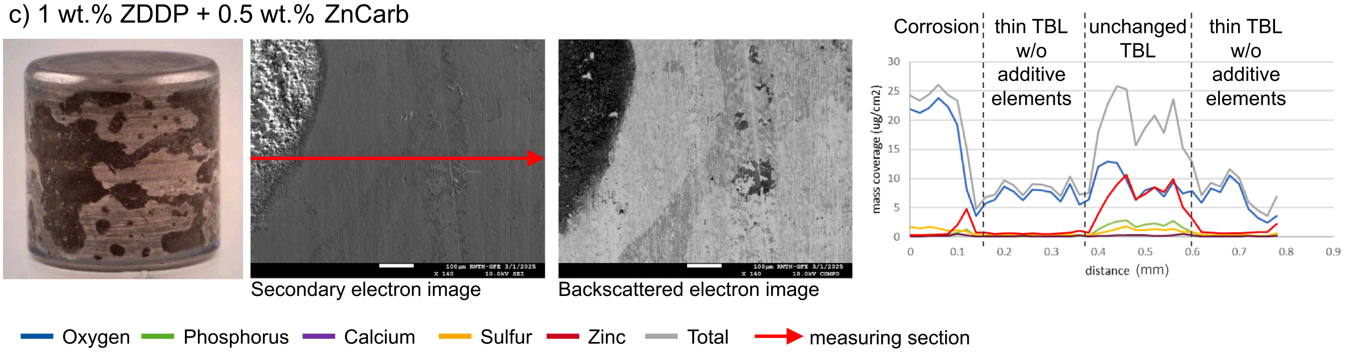
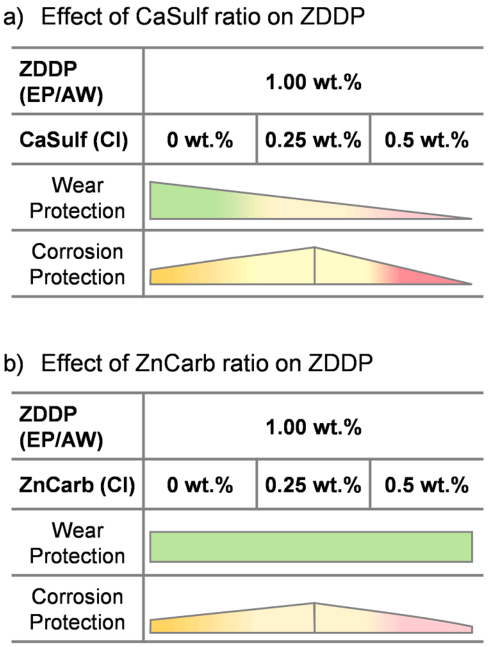


**Fig. 8.** EPMA results after corrosion test.



a) Effect of CaSulf ratio on ZDDP

| ZDDP (EP/AW) | 1.00 wt.% | | |
|---|---|---|---|
| CaSulf (CI) | 0 wt.% | 0.25 wt.% | 0.5 wt.% |
| Wear Protection | | | |
| Corrosion Protection | | | |

b) Effect of ZnCarb ratio on ZDDP

| ZDDP (EP/AW) | 1.00 wt.% | | |
|---|---|---|---|
| ZnCarb (CI) | 0 wt.% | 0.25 wt.% | 0.5 wt.% |
| Wear Protection | | | |
| Corrosion Protection | | | |

**Fig. 9.** Correlation of wear and corrosion protection of ZDDP when adding a) calcium sulfonate and b) zinc carboxylate.

1 wt% ZDDP. In addition, the ratio of 1:4 should be clarified for further EP/AW concentrations, e.g. 0.125 wt% CI to 0.5 wt% EP/AW and tests with other EP/AW additives need to be conducted for transferability to other additive combinations. Additionally, a more detailed determination of the corrosion level following the Corrosion Protection Test would be advantageous. Consequently, further research is needed to explore the image processing techniques for identifying corroded surfaces with varying visual characteristics of TBL.

## Statement of Originality

On behalf of my co-authors, I declare that the work described in the manuscript “Wear and corrosion protection in rolling element bearings – influence of ratio between extreme pressure / anti wear additive and corrosion inhibitor” has not been published previously in any other journal and neither is under consideration for publication in any other journal.

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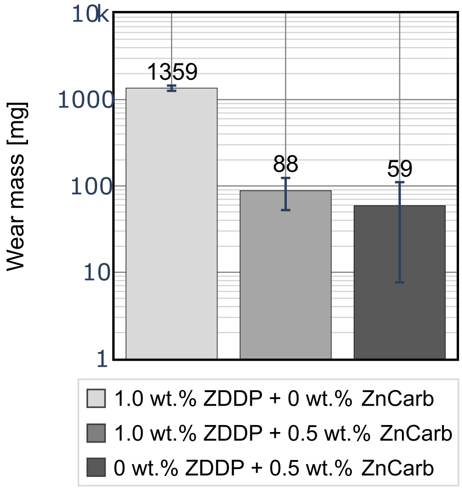
a) ***wear test*** *(n = 7.5 min$^{-1}$)*



b) ***EPMA results***

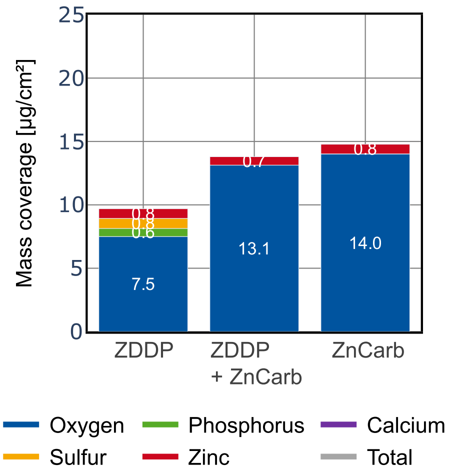


**Fig. 10.** Results of additional a) wear test and b) corresponding EPMA with sole ZnCarb.

Supported by:

## Appendix

Federal Ministry
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IGF

on the basis of a decision
by the German Bundestag

### CRediT authorship contribution statement

**Merle Reimers:** Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Silvia Richter:** Writing – original draft, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Georg Jacobs:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Marius Bürger:** Writing – review & editing, Conceptualization. **Florian König:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

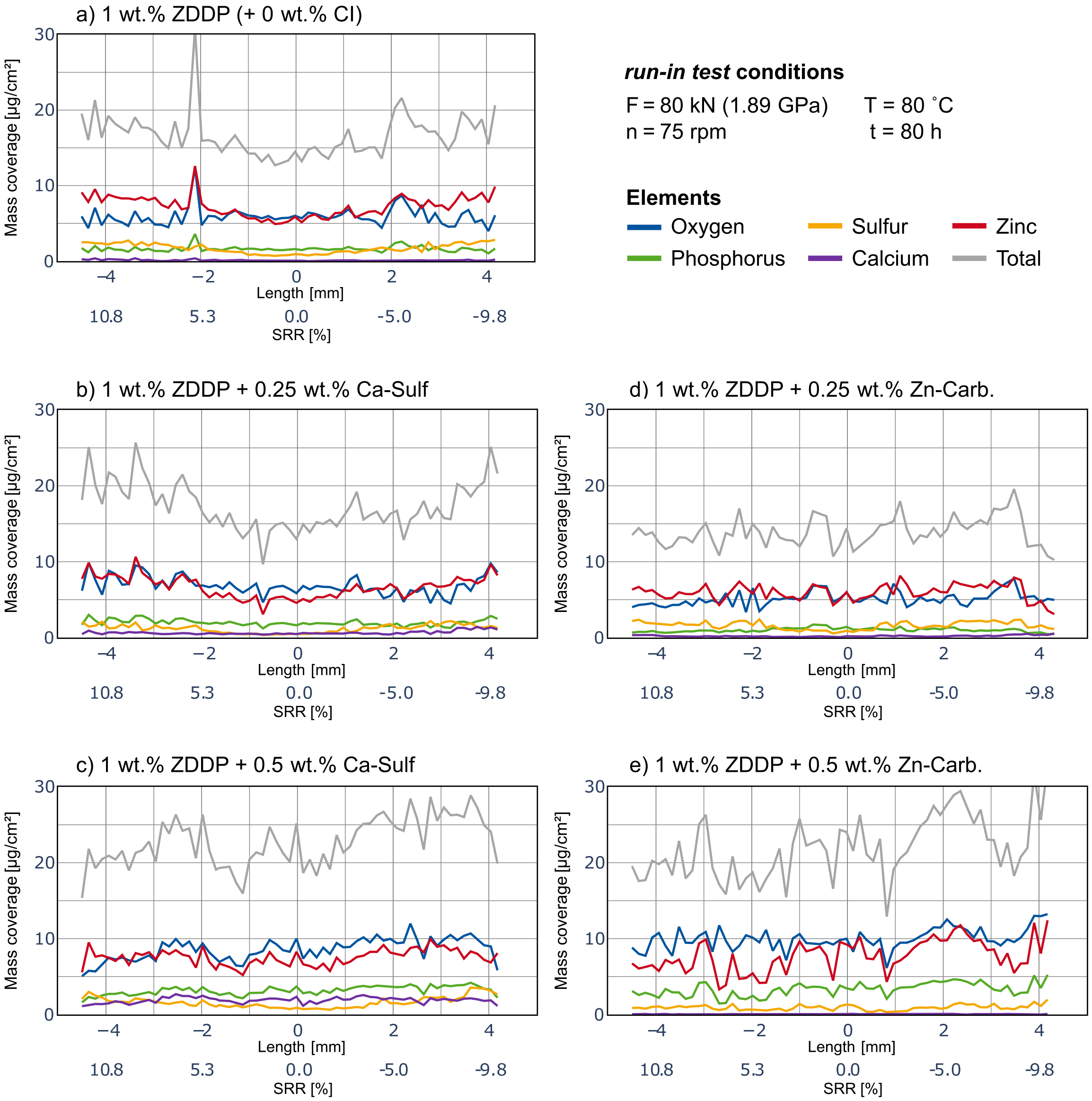

**Fig. 11.** EPMA line scan of TBL formed in run-in test

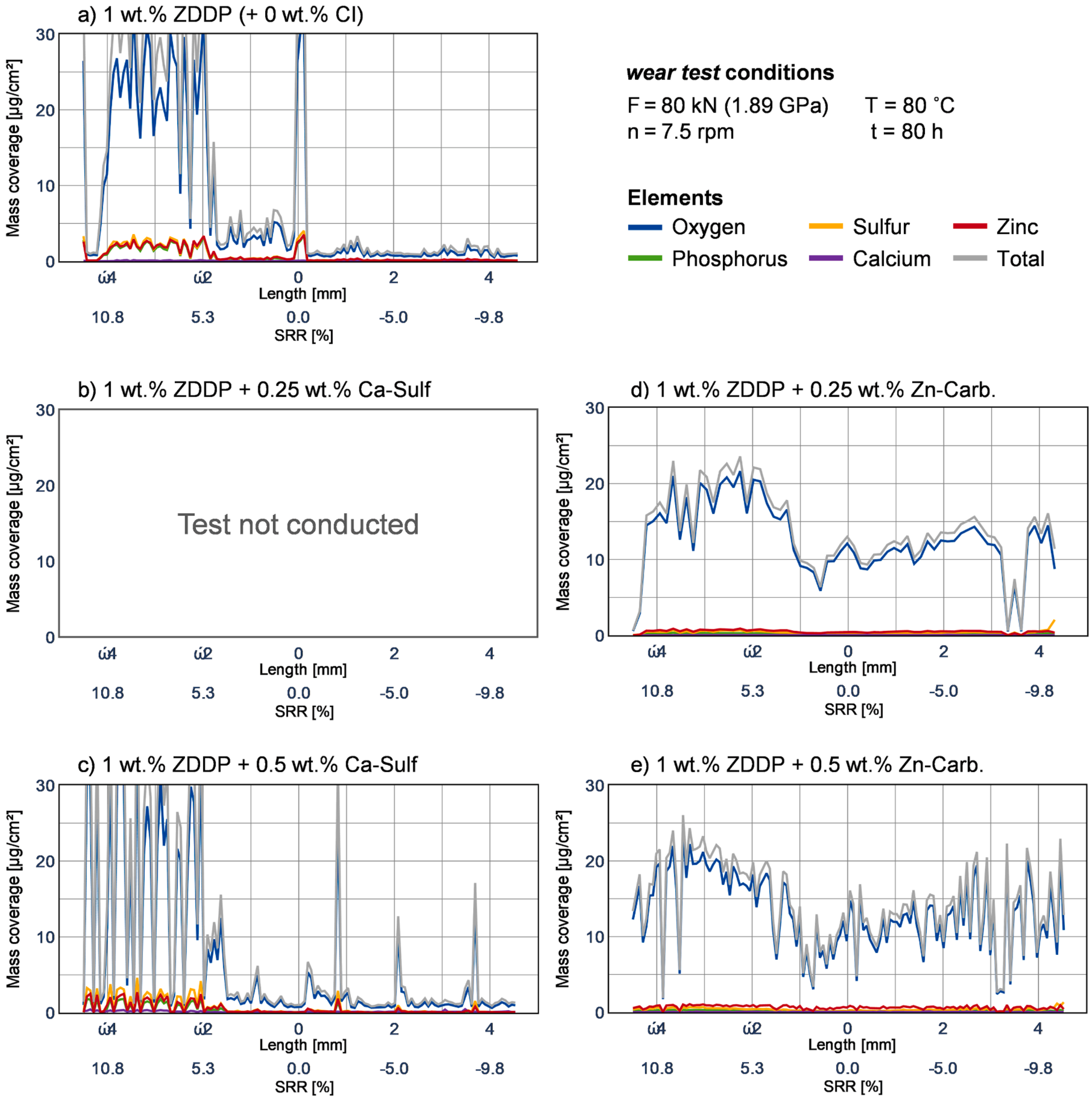

**Fig. 12.** EPMA line scan of TBL formed in wear test

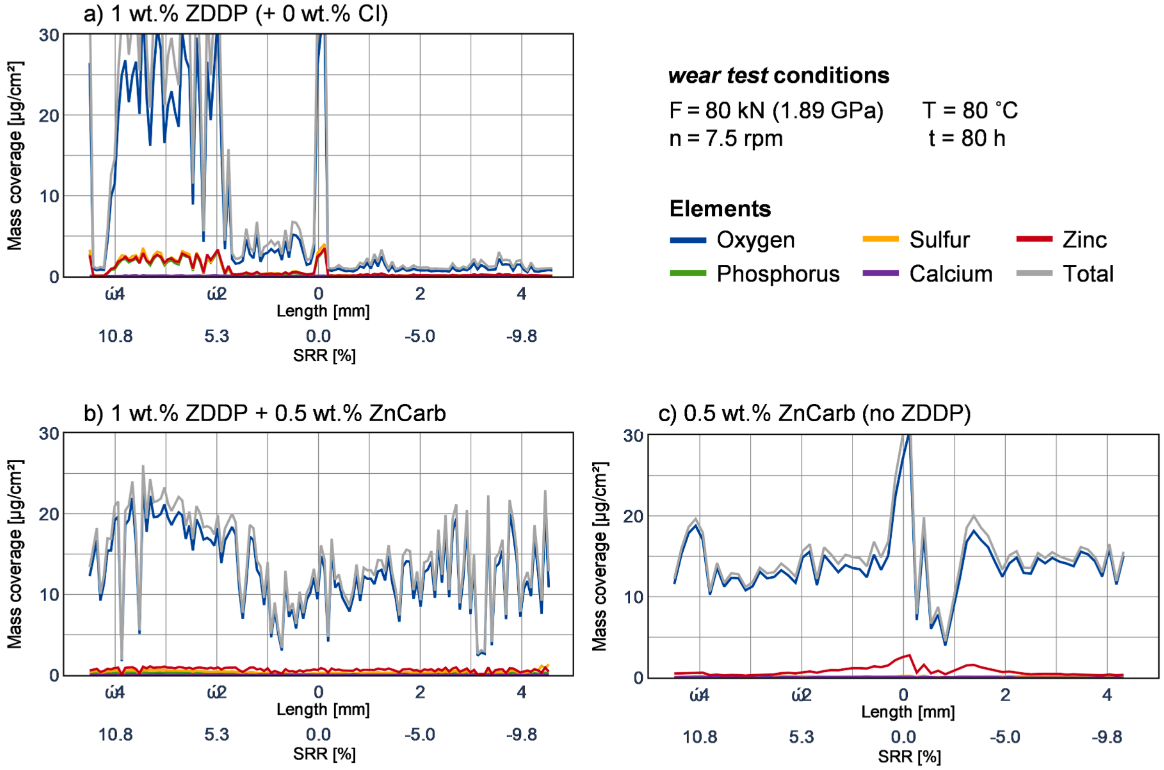

**Fig. 13.** EPMA line scan of TBL formed in wear test for additional test with sole ZnCarb

## Data availability

Data will be made available on request.

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